Ultra-low-power wireless transmitter for neural prostheses with modified pulse position modulation

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An ultra-low-power wireless transmitter for embedded bionic systems is proposed, which achieves 40 pJ/b energy efficiency and delivers 500 kb/s data using the medical implant communication service frequency band (402–405 MHz). It consumes a measured peak power of 200 µW from a 1.2 V supply while occupying an active area of 0.0016 mm^2 in a 130 nm technology. A modified pulse position modulation technique called saturated amplified signal is proposed and implemented, which can reduce the overall and per bit transferred power consumption of the transmitter while reducing the complexity of the transmitter architectures, and hence potentially shrinking the size of the implemented circuitry. The design is capable of being fully integrated on single-chip solutions for surgically implanted bionic systems, wearable devices and neural embedded systems.

1. Introduction: In biomedical applications, especially implanted medical devices (IMD) and neural prostheses (NP), the wireless transmission of data is desirable to minimise the number of wires through skin that can act as a conduit for antigens and bacteria. Two important aspects of wireless transceivers, for biomedical applications, are power consumption and size of the implant [1, 2]. The choice of modulation scheme and transceiver architecture extensively influences these features. This has led to a significant research effort towards reducing the overall power consumption and area occupied by such devices [1–6]. Also, since the energy sources for such devices should also occupy a small area (<25 mm^2), the peak power available from such sources is also restricted (<5 mW). Hence, not only the wireless transmitter needs to demonstrate energy-efficient figures for data transmission, but the peak power is also required to be below the peak power by a typical factor of ten (500 µW) to allow efficiency degradation from antenna, the interface, leakage and other circuitry deficiencies (10% total efficiency).

This Letter demonstrates the possibility of low-power, low-complexity transmitters with suitable energy efficiency and data rate for emerging NP by exploiting a modified modulation scheme called saturated amplified signal (SAS) [6]. This modulation is briefly explained in the following Section and is followed by the transmitter circuit design and measurement results from the implementation.

2. Saturated analogue signal modulation: In biomedical applications and neural embedded systems, to achieve low-power consumption, generally a less spectral efficient modulation scheme is used such as BFSK, BPSK or OOK. Researchers have been utilising ultra-wideband (UWB) and impulse radio (IR) systems exploiting high-frequency (3.1–10.6 GHz) short pulses to transmit bursts of data and achieve energy-efficient transmitters [2, 5]. The drawbacks of such systems are: (i) the necessity of a high peak power (a few mili-watts) transmitter and (ii) very short (up to a few cm) transmission ranges in the tissue because of absorption of higher frequency signals. By modifying the basic pulse position modulation (PPM), our proposed modulation scheme, called the SAS, employs relatively short pulses (with regards to BFSK and BPSK) in the MICS frequency band (401–406 MHz) for much better body penetration and benefits the same duty cycling advantages of UWB systems. The transmitter inherits the flexibility of the modulation, enabling it to dynamically trade power consumption with data rate and range. This modulation increases the bandwidth of the transmitted signal and hence the noise bandwidth but, since the receiver architecture for SAS compensates for noise performance penalty and the overall power consumption and size benefits outweigh this performance loss, the final results show better energy efficiency and smaller implementation size in both the transmit and receive sides [6].

3. Transmitter design: Utilising SAS modulation, the architecture of the transmitter is reduced to a frequency generation block combined with the digital circuitry for modulation symbol generation and a mixer, which will act as the driving stage of the antenna and be matched to the antenna by utilising bondwires and on-chip capacitances (Fig. 1*b*). This is similar to direct modulation architecture in UWB systems and enables the possibility of duty cycling the transmitter. Avoiding the power amplifier at the output stage reduces the available power delivered to the antenna and total efficiency of the transmitter, but since the transmitter is designed for biomedical applications, the output power is bounded to −16 dBm by MICS regulations.

Data modulation is performed by dividing the duration of each data bit (500 kb/s rate) into a predefined number of smaller, equal portions called bins. To encode each data bit, a single-frequency sinusoid signal (403 MHz in our transmitter) will appear in some of the bins. An example of such signal (with 6% duty cycling) is defined in (1) and has been shown together with the power spectral density (PSD) of this signal in Fig. 2. The MICS frequency band (402–405 MHz) has also been shown as an overlay to show the compatibility of this modulation for the designed frequency band.

The digital section generates the modulation symbols (combinations of bins) according to each data bit and has the following inputs: (i) data (at up to 500 kbps); (ii) the duty cycle period (1–95%); (iii) the number of bins for each 0 or 1 logic and; (iv) the carrier frequency as a clock. The number of bins can be changed to suit various bandwidth and data rate requirements. This number also defines the energy per bit consumption and duty cycling period of the transmitter and can be increased to achieve a more robust reception. Duty cycling of the transmitter is realised through power gating of the frequency

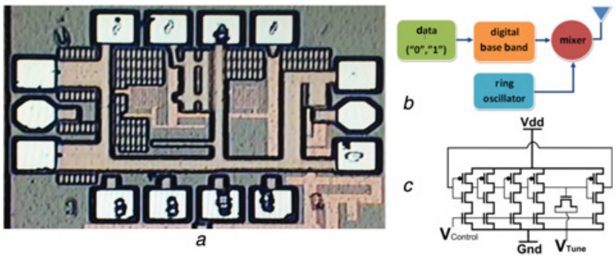

Figure 1
a Die micrograph of the transmitter chip
b Transmitter architecture (matching not shown)
c RO with control voltages

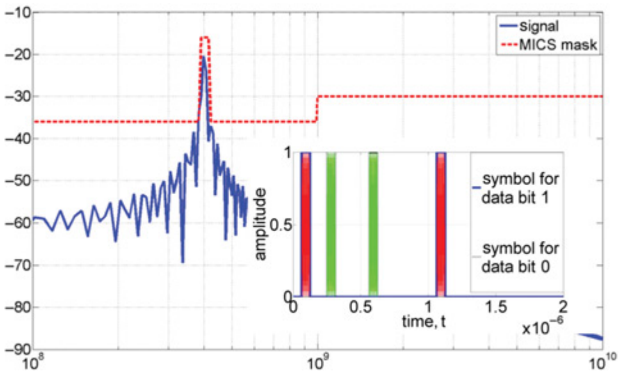

Figure 2 *PSD of random SAS modulated sequence and overlaid MICS spectrum mask*
Inset: SAS modulation symbols for bit 0 and 1

generation and mixer circuitry. This Section has been produced using Verilog coding and standard cells in 130 nm technology.

Since SAS demodulation is based on the position and number of the bins within each symbol, sinusoid signal frequency in each bin can vary in an acceptable MICS frequency range during operation. Also, as the transmitter is designed for IMDs and NPs, the environment temperature of the device is well regulated by the body and the infrequent changes happen very gradually. As such, an inverter chain ring oscillator (RO) is implemented as the frequency generation block with some coarse tuning capabilities utilising current control of the ring and a variable MOS capacitor to obtain a 402 MHz oscillation frequency (Fig. 1*c*). A transmission gate passive mixer generates the output signal, which further decreases the power consumption of the transmitter. Utilising SAS modulation, the architecture of the transmitter is reduced to a frequency generation block combined with the digital circuitry for modulation symbol generation and a mixer, which will act as the driving stage of the antenna and is matched to the antenna by utilising bondwires and on-chip capacitances (Fig. 1*b*).

This is similar to direct modulation architecture in UWB systems and enables the possibility of duty cycling the transmitter. Avoiding the power amplifier at the output stage reduces the available power delivered to the antenna and total efficiency of the transmitter, but since the transmitter is designed for biomedical applications, output power is bounded to −16 dBm by MICS regulations. Data modulation is performed by dividing the duration of each data bit (500 kb/s rate) into a predefined number of bins. To encode each data bit, a single-frequency sinusoid signal (403 MHz in our transmitter) will appear in some of the bins.

An example of such a signal (with 6% duty cycling) is defined as follows, and has been shown together with the PSD of this signal in Fig. 2. The MICS frequency band (401–406 MHz) has also been shown as an overlay to show the compatibility of this modulation for the designed frequency band.

$$g(t)=\begin{cases} A\cos(2\pi f_c t)\,\mathrm{rect}\left(\dfrac{t-(2T/32)}{(T/32)}\right)+A\cos(2\pi f_c t)\,\mathrm{rect}\left(\dfrac{t-(18T/32)}{(T/32)}\right), & a_k=1\\ A\cos(2\pi f_c t)\,\mathrm{rect}\left(\dfrac{t-(5T/32)}{(T/32)}\right)+A\cos(2\pi f_c t)\,\mathrm{rect}\left(\dfrac{t-(10T/32)}{(T/32)}\right), & a_k=0\end{cases} \quad (1)$$

4. Measurement results: The transmitter performance was measured in free space as well as in an immersed topology, where the transmitter was immersed in a saline solution and tested. Since the modulation technique used in this work is unique, to demodulate and receive the data, a special receiver utilising the same SAS principles have also been designed and fabricated but the reported measurements in this work are derived from a receiver, built by utilising off-the-shelf components.

The transmitter performance has been summarised in Table 1 and also some state-of-the-art transmitters from the literature have been compared with this work. As can be seen, the transmitter achieves the best energy efficiency (40 pJ/b with 10% duty cycling) among the others while maintaining the same communication range and acceptable output power. The resulting digital block consumes 60 μW of power from a 1.2 V supply when operating at 500 kbps with a 402 MHz carrier frequency.

Transmitter power would increase with bin duration as expected and hence the transmitter can trade off the transmission power and range with the energy efficiency and data rate. Fig. 3 illustrates the simulation and measurement results of the transmitter power as a function of bin duration.

Table 1 Transmitter performance comparison

Reference	[1]	[2]	[3]	[4]	[5]	This work
transmit power, dBm	11	−10	N/A	−5	−12	−20
range, m	4	20	0.01	2	3	5
average power, pJ/b	1500	5916	343	1600	52	40
peak power, mW	21	142	3.5	1.6	0.52	0.2
data rate, Mbps	14	24	10.2	0.1	10	0.5
chip area, mm^2	0.18	784	1.8	>7.8	1.76	0.53
technology, nm CMOS	500	COTS[a]	500	180	350	130

[a]Components off-the-shelf

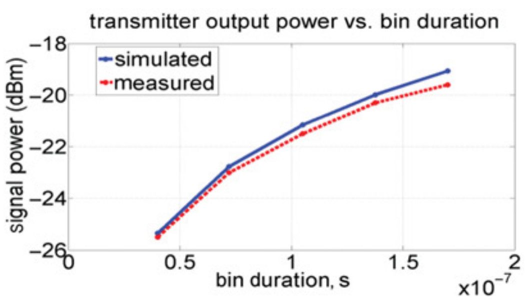

Figure 3 *Transmitter output power was measured for different bin durations and output power increases with bin duration*

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5. Conclusion: In this Letter, a transmitter, suitable for IMD and NP, has been introduces and analysed. The transmitter consumes a peak power of 200 µW from a 1.2 V supply to achieve 500 kbps data rate at −20 dBm output power. An energy efficiency of 40 pJ/b is measured by exploiting 10% duty cycling at 5 m range. The transmitter is designed in the MICS frequency band (402–405 MHz) and has been laid out in 130 nm technology while occupying an active area of 35 by 45 µm and a total chip area (including test pads) of 0.53 mm^2.

Also in this Letter, a previously defined modulation, SAS, is exploited, which provides the transmitter with a simplified architecture, better energy efficiency and reduced die area. The modulation also benefits an inherent flexibility, which provides transmitter with the possibility of working in different environments since the modulation can trades off energy consumption, duty cycling, range and data rate.

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